

Nutrient Fluxes in Forests of the Eastern Sierra Nevada: Comparisons with Humid Forest Systems¹

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Abstract

Preliminary results of studies on nutrient fluxes in forests of the eastern Sierra Nevada were compared to those from more humid and polluted ecosystems. Snowmelt, soil solution, soil, and streamwater were collected from Jeffrey and lodgepole pine (*Pinus jeffreyi* [Grev. and Balf.] and *Pinus contorta* Dougl.) stands in Little Valley, Nevada, and from California red fir (*Abies magnifica* A. murr.) and Jeffrey pine/white fir (*Pinus jeffreyi*/Abies concolor [Gord and Glend.] Lindl.) stands at Sagehen, California. Snowmelt, soil solutions, and streamwaters from both sites were circumneutral and dominated by base cations and bicarbonate. The red fir stand at Sagehen had high NO_3^- concentrations (approximately 30-100 $\mu\text{mol/L}$) in both snowmelt and soil solution during the relatively dry 1993-4 water year. The Little Valley sites had substantially lower NO_3^- concentrations in both snowmelt (5-20 $\mu\text{mol/L}$) and soil solution (0.5-3 $\mu\text{mol/L}$) in both wet and dry years. At both sites, a pulse of streamwater NO_3^- (from 0.5 to 20-40 $\mu\text{mol/L}$) was detected during dry years but not wet years. The Andic soils at the Sagehen site have trace levels of available P in soils, whereas the Entisols and Inceptisols in Little Valley have 10 to 100 times greater levels. The results suggest a hypothesis that the greater mobility of NO_3^- in the Sagehen red fir site was caused by the amount and timing of NO_3^- release from snowmelt (e.g., too concentrated and early for dormant biota to respond to), and that P may also be limiting at Sagehen. Compared to other forest ecosystems in more humid and polluted environments, N, S and H⁺ deposition and fluxes at the Little Valley site are extremely low, but HCO_3^- and base cation fluxes are high. This reveals that the Little Valley site is relatively pristine, and that ionic fluxes at this site are dominated by natural carbonic acid leaching and weathering reactions.

Introduction

In comparison to more humid regions, information about nutrient cycling in forests of arid and semi-arid regions is scant. Some nutrient cycling work has been done on ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) (Hart and Firestone 1989, Klemmedson 1975) and lodgepole pine (*Pinus contorta* Dougl.) ecosystems (Fahey 1983, Fahey and Knight 1986, Schimel and Firestone 1989), but these studies are relatively fewer than those in more humid regions (Cole and Rapp 1981, Johnson and Lindberg 1991). Except for Stark's (1973) study on Jeffrey pine (*Pinus jeffreyi* Grev. and Balf.), little is known about the cycling of nutrients in forests of the eastern Sierra Nevada.

Scientific knowledge of nutrient cycles in forests of the eastern Sierra Nevada should be increased for several reasons. First, this knowledge would allow intelligent assessments of forest management practices such as harvesting, burning, and site preparation as well as the effects of exogenous influences such as fire, air pollution, and climate change on these forests. Second, these forests act as filters for nutrients, especially nitrogen, which might otherwise enter the sensitive surface waters of the region. The long-term deterioration of water quality of Lake Tahoe has been clearly documented (Goldman and others 1983). This deterioration is thought to be caused by increasing nutrient inputs from land development, atmospheric deposition, and N fixation by riparian mountain alder (*Alnus tenuifolia* Nutt.) (Byron and Goldman 1989, Coats and others 1976, Leonard and others 1980). With N and H⁺ inputs increasing in the Tahoe Basin (Byron and others 1991), it is important to gain some knowledge of the capacity of forest ecosystems in the basin to filter these inputs. Galloway and others (1995) forecast that anthropogenic N fixation (by a combination of energy production, fertilizer production, and cultivation of N-fixing crops) will increase by about 60 percent by the year 2020. They predict that about two-thirds of this increase will take place in Asia, which

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by 2020 will account for over half of the global anthropogenic N fixation. Thus, there is the potential for increased N deposition in western North America from both local and long-range sources. At the same time, the capacity of forests to retain N has been reduced because of increased insect- and drought-induced mortality and from fires.

This paper reports progress to date on studies of nutrient cycling in forests of the eastern Sierra Nevada, and compares these results with those from a variety of forest ecosystems in more humid climates by using the Integrated Forest Study database on forest nutrient cycling (Johnson and Lindberg 1991).

Sites and Methods

The Little Valley site is located about 30 km southwest of Reno, Nevada in the eastern Sierra Nevada (*fig. 1*). It ranges from 2,010 to 2,380 m elevation. Vegetation is dominated by lodgepole pine in riparian areas, Jeffrey pine at lower elevations and white fir (*Abies concolor* [Gord and Glend.] Lindl.) at higher elevations. Mean annual temperature (MAT) near the valley floor is 5 °C and mean annual precipitation (MAP) is 550 mm, about 50 percent of which falls as snow. Site 1 in the northern end of the Valley is located on the Corbett series soil, a typical frigid Xeropsamment derived from outwash of decomposed granite. Overstory vegetation consists of Jeffrey pine with an occasional white fir. Understory vegetation is absent. Site 2 is located about 5 km south of site 1 on Marta series soil, a sandy, mixed Aquic Cryumbrept derived from colluvium of decomposed granite. Overstory vegetation in site 2 consists of lodgepole pine with occasional Jeffrey pine. Understory vegetation consists of sage (*Artemisia tridentata* Nutt.) and various grasses and forbs.

The Sagehen Creek watershed is located about 10 km north of Truckee, California (*fig. 1*). Elevation ranges from 1,830 to 2,500 m elevation. MAP and MAT at the Sagehen field station (elevation = 1,830 m) are 870 mm and 4.8 °C, respectively. More than half of total precipitation falls as snow. Site 1 is located on Waca series soil, a loamy skeletal, mixed, frigid Andic Xerochrept derived from andesitic lahar and tuff. Overstory vegetation consists of 80-160-year-old California red fir (*Abies magnifica* A. murr.) with occasional white fir and an understory of pinemat manzanita (*Arctostaphylos nevadensis* Gray) with *Ribes* and *Wyethia* spp. Elevation at the site is 2,100 m. Site 2 is located on Fugawee series soil, a fine-loamy, mixed frigid Ultic Haploxeralf derived from andesitic lahar and tuff. Overstory vegetation consists of 80-160-year-old Jeffrey pine and white fir. Understory consists primarily of occasional *Ribes* and squaw carpet (*Ceanothus prostratus* Benth.).

Over a 6-year period (1989 - 1995), we collected snowmelt, soil solutions, and streamwater from various sites. Because of a combination of fiscal and logistical limitations, we could not collect solutions from all sites simultaneously. Thus, solutions were collected from Site 1 in Little Valley during the relatively droughty 1989-90 water year, from Site 1 at Sagehen site during the relatively droughty 1993-94 water year, and from Site 2 at Little Valley during the relatively wet 1994-95 water year. We attempted to collect from Site 1 at Sagehen during 1994-95, also, but the deep snowpack (as much as 5 m) there during that year precluded consistent water collections.

Snowmelt collectors and tube-type tension lysimeters were located in six randomly located positions within a 0.05-ha plot at each site. Snowmelt collectors consist of buried collection bottles to which the open collectors are attached. The open collectors sit on the ground surface partially buried and consist of the cut-off tops of polypropylene bottles fitted with a drainage tube that is attached to the buried collection bottle. These devices collect rain or throughfall (depending upon their location) during the snow-free seasons and snowmelt during the snow season. The collection bottle is fitted with tubing that is run-up poles so that collections of snowmelt solutions are possible from beneath snowpack without disturbance.

Tube-type lysimeters are fitted with an extra tube which, along with a vent tube, allows removal of soil solutions from under snowpack without disturbance (Johnson 1995). All solutions were analyzed for conductivity, pH and alkalinity (titration to pH 5.0), cations (Ca^{2+} , Mg^{2+} , K^+ , Na^+ , NH_4^+) by Dionex ion chromatography,⁶ anions (Cl^- , NO_3^- , ortho phosphate, SO_4^{2-}) by Dionex ion chromatography, and Si by ICP spectroscopy.

We used the chloride balance method (Lindberg and Johnson 1989) to estimate nutrient fluxes at Little Valley. (Because of an insufficient number of reliable snowmelt water volume collections at the other sites, these calculations were not made). Chloride fluxes were measured directly from water volumes and concentrations in the snowmelt collectors beneath the forest canopy. We used these rather than the open collectors in order to better incorporate dry deposition of Cl into the calculations. It was then assumed that Cl fluxes through the soil were equal to amounts from snowmelt (i.e., that Cl was a conservative tracer), and soil water fluxes were calculated from this. These water fluxes were then used with soil solution concentrations to estimate soil leaching rates for the various ions.

Figure 1 — Research sites were located at Little Valley, Nevada, and Sagehen, California.



⁶ Mention of trade names or products is for information only and does not imply endorsement by the U.S. Department of Agriculture.

Results and Discussion

In previous studies in Little Valley (Site 1), we followed up the studies of Coats and others (1976) in the Tahoe Basin and investigated the effects of N fixation by both mountain alder (*Alnus tenuifolia* Nutt.) and snowbush (*Ceanothus velutinus* Dougl.) on soils and soil solutions in comparison to Jeffrey pine. (We know of no previous studies have been conducted on soil solution chemistry beneath snowbush.) In contrast to the results of Coats and others (1976), we found no evidence of excess NO_3^- beneath either mountain alder or snowbush during the 1989-90 water year. Soil solution NO_3^- concentrations were near trace levels under all three species (table 1; Johnson 1995). We found a sizable NO_3^- peak in streamwaters from nearby Franktown Creek during snowmelt in 1990 (a dry year) (fig. 2) but not in 1995 (a wet year). Sulfate, HCO_3^- , total cation and total anion concentrations in Site 1 in Little Valley were quite high. Sulfate and Cl^- concentrations in soil solutions were two orders of magnitude greater than in nearby streamwaters (Johnson 1995). More recent studies (1994-95 water year) in a lodgepole pine stand growing on more weathered soil lower in the valley (Site 2) showed similarly low soil solution NO_3^- concentrations, but also much lower SO_4^{2-} , Cl^- , total cation and anion concentrations than in the original site. At this stage, we do not know the reasons for the differences in soil solutions between these two sites, but possibilities include the age of the parent material and the amount of water flux. The parent material in Site 1 consisted of alluvium from nearby Ophir Creek and is noticeably less oxidized than that in Site 2. Research is underway to determine the reasons for these differences.

Snowmelt and soil solutions from the red fir stand (Site 1) at Sagehen were similar to those from Site 2 in Little Valley in terms of pH, HCO_3^- , SO_4^{2-} , total

Table 1 — Concentrations of selected ions in soil solutions and streams from Little Valley, Nevada, and Sagehen, California.¹

	pH	HCO_3^- $\mu\text{mol L}^{-1}$	NH_4^+	SO_4^{2-}	Cation	Anions
Little Valley:						
Site 1²						
Soil solution						
Ceanothus	6.7 ± 0.1	306 ± 47	3 ± 3	107 ± 15	1107 ± 129	614 ± 113
Pine	7.1 ± 0.1	417 ± 94	<0.5	273 ± 46	1098 ± 200	842 ± 75
Mt. Alder	7.0 ± 0.2	688 ± 192	<0.5	181 ± 59	1084 ± 315	1017 ± 296
Stream	7.1 ± 0.2	373 ± 15	3 ± 2	3 ± 0.2	373 ± 12	396 ± 15
Site 2						
Snowmelt						
	6.0 ± 0.3	102 ± 88	4 ± 6	15 ± 18	337 ± 203	143 ± 104
Soil solution						
15 cm	6.4 ± 0.4	260 ± 257	0.2 ± 0.6	10 ± 25	514 ± 328	292 ± 255
30 cm	6.6 ± 0.4	281 ± 138	0.2 ± 0.5	7 ± 6	501 ± 109	328 ± 125
Stream	6.8 ± 0.4	389 ± 30	0.5 ± 1.0	11 ± 12	579 ± 77	419 ± 48
Sagehen Creek:						
Site 1						
Snowmelt						
	6.8 ± 0.2	125 ± 75	64 ± 60	13 ± 8	340 ± 120	231 ± 93
Soil solution						
15 cm	7.2 ± 0.7	300 ± 111	64 ± 48	19 ± 12	693 ± 297	408 ± 129
30 cm	7.3 ± 0.3	407 ± 283	48 ± 33	20 ± 16	702 ± 329	505 ± 301
Stream	7.4 ± 0.4	977 ± 440	19 ± 21	2 ± 1	1280 ± 219	1006 ± 429

¹ Standard errors are given.

² Johnson (1995).

cations and total anions, but were considerably higher in both NO_3^- and NH_4^+ (table 1). (Snowmelt and soil solution data from Site 2 at Sagehen are being collected in the 1995-96 season and are not yet available.) Sagehen Creek showed a peak in NO_3^- during snowmelt in a drought year (1993-94) but not in a wet year (1994-95) (fig. 3). At both Little Valley Site 2 and Sagehen Site 1, snowmelt NO_3^- peaked during the spring of 1994 and 1995 (fig. 4). But the two sites differed: the peak NO_3^- concentrations at the Sagehen site were an order of magnitude greater than at Little Valley Site 2, and the pulse of NO_3^- at Sagehen penetrated the soil whereas this was not the case in Little Valley Site 2. The same patterns were apparent in NH_4^+ release from snowpack and mobility at these two sites (not shown). Differences in snowpack amounts, snowmelt NO_3^- and NH_4^+ concentrations, the timing of NO_3^- and NH_4^+ release from snowpack NH_4^+ , and site conditions could contribute to these differences in NO_3^- and NH_4^+ mobility at the two sites. At Sagehen Site 1, peak snowmelt NO_3^- was much higher and occurred earlier (March-May) than at Little Valley Site 2 (May-June). Only in June, when snowmelt NO_3^- concentrations decreased and biological N uptake presumably commenced, did soil solution NO_3^- at Sagehen Site 1 drop to levels typical of N deficient ecosystems. The same patterns were apparent for NH_4^+ (not shown).

Currently, we are entertaining two alternative hypotheses to explain the differences in N- mobility in the Little Valley and Sagehen sites. The first hypothesis is that there is a temporal decoupling of N release from melting snowpack and

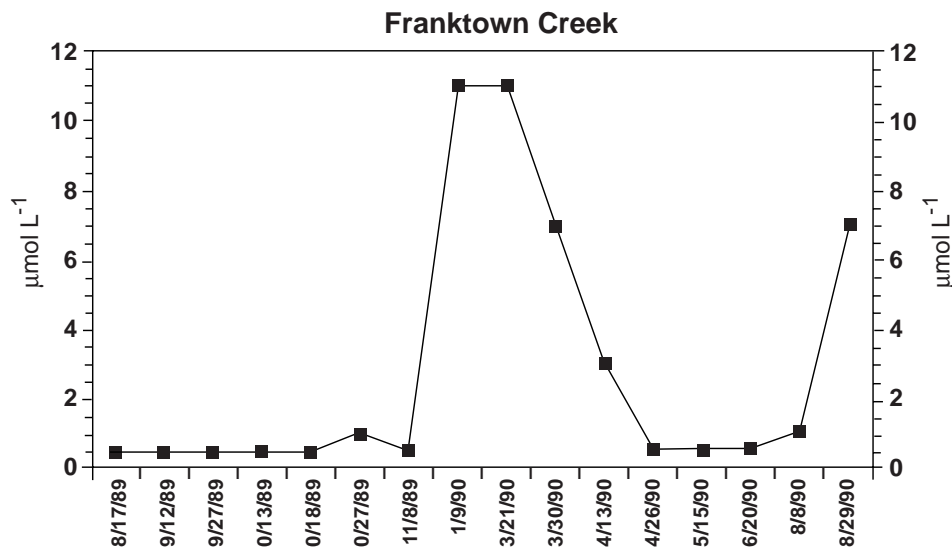


Figure 2 — Temporal patterns in NO_3^- concentration in Franktown Creek, Little Valley, Nevada.

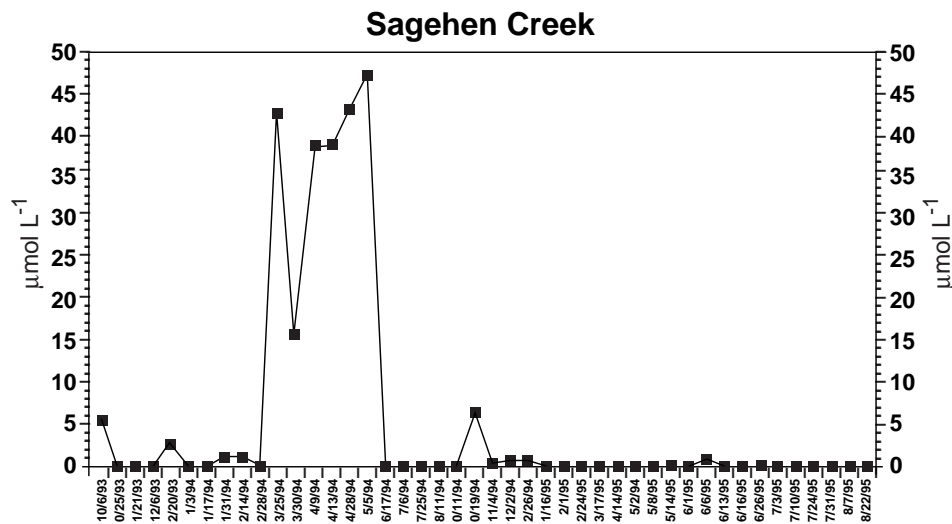
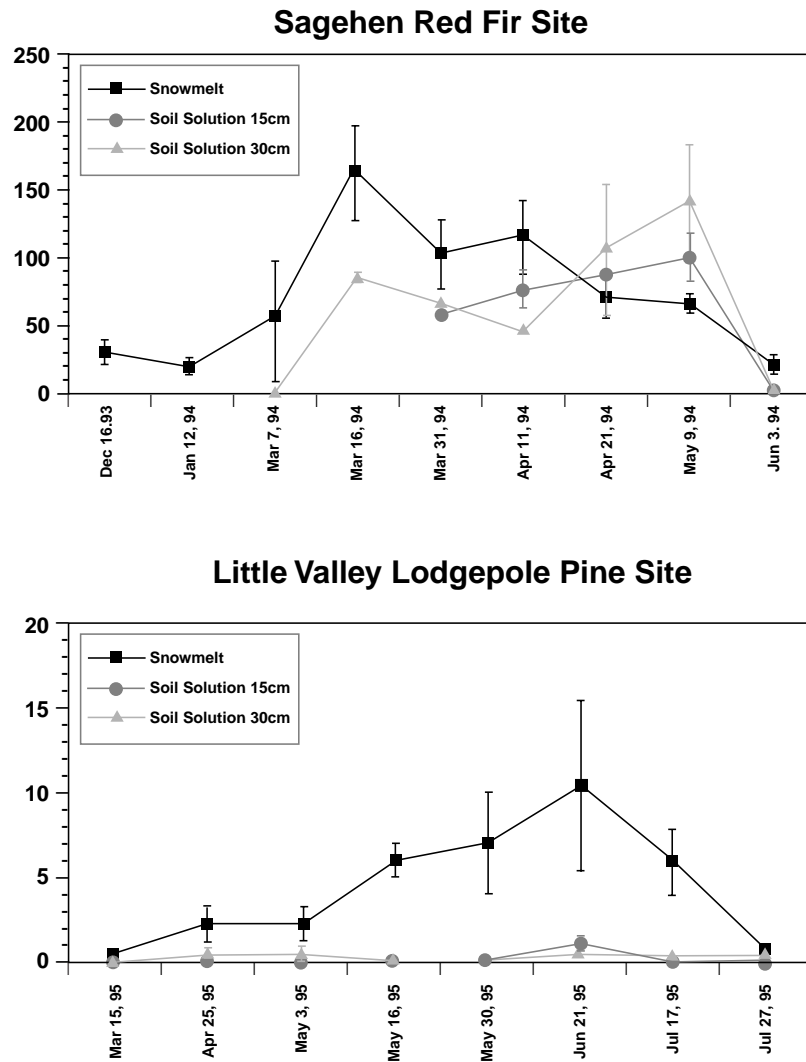


Figure 3 — Temporal patterns in NO_3^- concentration in Sagehen Creek, California.

the activation of biological uptake in these systems. In Mediterranean ecosystems like these, when soil moisture conditions are most favorable for biological activity (winter/spring), the soil and air temperatures may be limiting; when soil and air temperatures are most favorable (summer) for biological activity, soil moisture conditions are limiting. Thus, only during brief periods (e.g., after the snow pack melts and in the fall period before snow pack accumulates) is biological activity not severely inhibited by temperature and moisture conditions. We hypothesize that amount and timing of N release during snowmelt is critical to the mobility of N in the system. If snowmelt N release is concentrated and early, as apparently was the case at Sagehen in the droughty spring 1994, biota may not have broken dormancy sufficiently to take up N as it passed by. If snowmelt N release is more diluted and later, such as was the case in the wet spring 1995, there is a better chance for biotic uptake of N. We are currently testing this hypothesis by making simultaneous collections in the low-elevation pine-dominated stands (Site 2) at both Little Valley and Sagehen, where we are comparing and contrasting N mobility during wet and dry years.

The second hypothesis to explain the difference in N mobility in these two watersheds relates to the soil parent material and its effects on P status. The available P status of the Sagehen soils, which nearly fall into the Andisol order (known to have high phosphate adsorption capacity), is low compared to the soils in Little Valley. Soils from Site 1 in Little Valley have extractable levels that are an order of magnitude greater than those typical of more humid region forest soils (Johnson and Lindberg 1991) (table 2). In the more weathered and oxidized soils in Site 2 in

Figure 4 — Snowmelt and soil solution NO₃⁻ in Sagehen Site 1 (top) and Little Valley Site 2 (bottom).



Little Valley, available P levels are in the range typically encountered in more humid forest soils. In contrast, extractable P in the Sagehen soils from two different sites are below detection limits (*table 2*). We hypothesize that high P fixation capacity on non-crystalline materials (e.g., ferrihydrite, allophane, imogolite, Al and Fe humus complexes) in the Andic soils at Sagehen has caused a potential P limitation. In contrast, we hypothesize that P levels in Little Valley Entisols and Inceptisols are high because of low contents of non crystalline materials and low P fixation capacity. We hypothesize that P limitation in the Sagehen sites limits the capability of these forests to take up N released during snowmelt. We are currently testing this hypothesis in part by performing single-tree N and P fertilization studies at both Little Valley and Sagehen. These fertilization trials and their associated vector analysis of foliage response have proven to be extremely reliable indicators of potential nutrient limitation in other coniferous forests (Timmer and Stone 1978).

We do not believe that the differences in N in the two sites are related to air pollution inputs. Chemical analysis of air (Bytnerowicz and Reichers 1995) was performed in August 1994 at the Sagehen and Little Valley sites (*table 3*). Concentrations of ammonia (NH₃), nitric acid vapor (HNO₃), and particulate nitrate (NO₃⁻) were about three times higher at the Little Valley site compared with the Sagehen site. The concentrations at the Little Valley site were similar to the values at the mixed coniferous forest locations near Kings Canyon, western Sierra Nevada (Bytnerowicz and Reichers 1995). HNO₃ concentration at Sagehen was about two times higher than the average summer concentration at the clean site of the eastern Sierra Nevada (Miller and Walsh 1991).

Table 2 — Soil extractable P (NH₄F/HCL) in Little Valley, Nevada, and Sagehen, California soils.¹

Little Valley ²		Sagehen	
Horizon and extr. P depth (cm)	Horizon and extr. P (µg g ⁻¹)	depth (cm)	(µg g ⁻¹)
Site 1		Site 1	
A (0-20)	101 ± 21	A (0-10)	<0.5
BA (20-40)	106 ± 36	B (10-18)	<0.5
BC (40-60)	69 ± 12	BC (18-45)	<0.5
Site 2		Site 2	
A (0-5)	10 ± 3	A (0-10)	0.3 ± 0.3
BA (5-20)	8 ± 3	B (10-18)	0.1 ± 0.1
BC (20-50)	4 ± 2	BC (18-45)	0.1 ± 0.1

¹ Standard errors are given.

² Johnson (1995)

Table 3 — Concentrations of selected nitrogenous air pollutants at two Sierra Nevada sites (µg m⁻³).¹

Location	NH ₃	HNO ₃	NO ₃ ⁻ particulate
Sagehen, California	0.347 (0.044)	0.636 (0.060)	0.149 (0.060)
Little Valley, Nevada	1.142 (0.099)	2.019 (0.212)	0.506 (0.039)

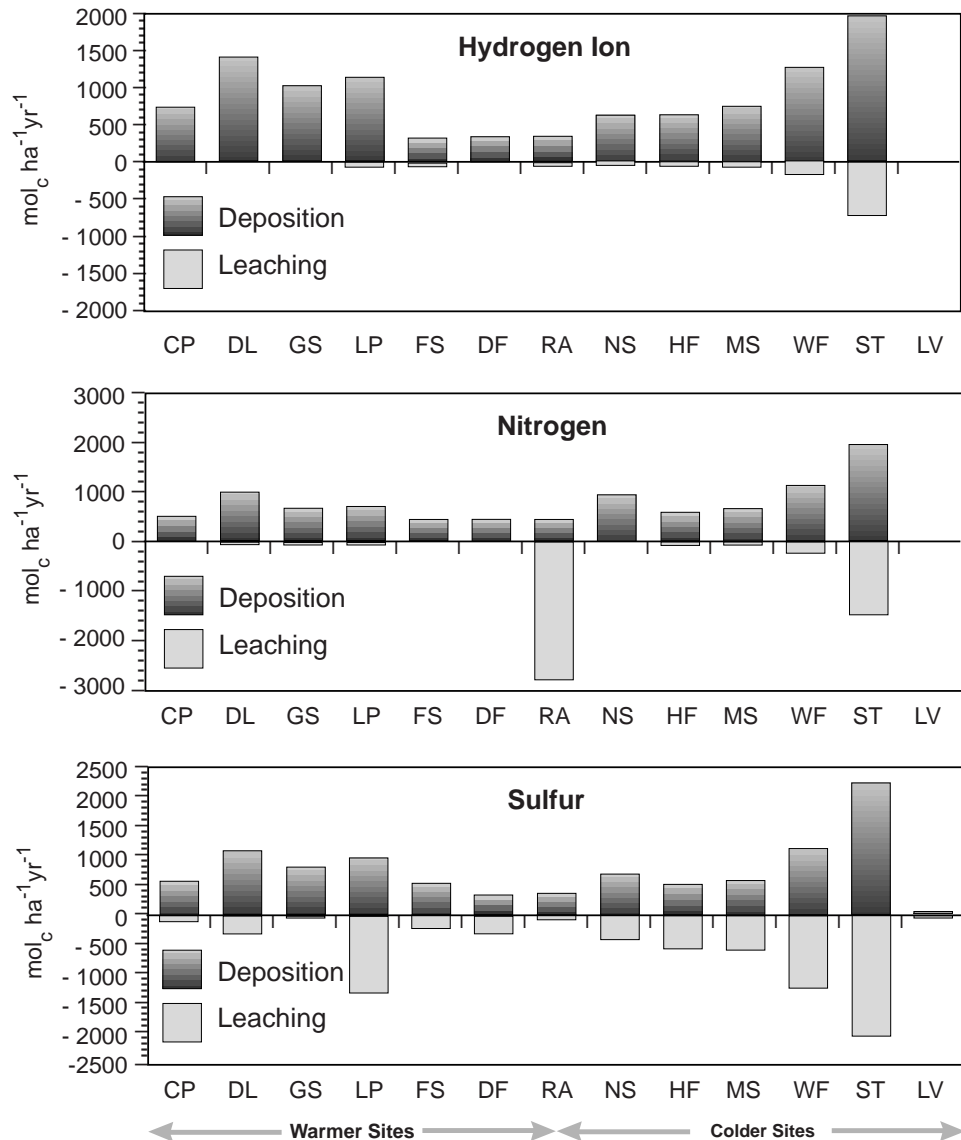
¹ Standard errors are given. Nitrogenous compounds were measured with annular denuder system (Bytnerowicz and Reichers 1995).

Comparison of Little Valley to Other Forest Ecosystems

Deposition and soil leaching fluxes of N, S, H⁺, and Ca²⁺, Mg²⁺, and HCO₃⁻ in Site 2 at Little Valley were compared to fluxes in a variety of forest ecosystems from the Integrated Forest Study (IFS) (figs. 5, 6). (Because of logistical problems and funding limitations, we have not been able to collect sufficient data to calculate fluxes for Site 1 in Little Valley or the Sagehen site as yet.)

Although the pulses of NO₃⁻ in the Little Valley and Sagehen sites are of concern in terms of water quality in the sensitive surface waters of this region, comparisons with the IFS sites clearly reveal that the Little Valley (LV) site is relatively pristine. The fluxes of H⁺, N, and S in LV are lower than those in the other systems, including the relatively unpolluted systems in the Pacific Northwest (DF and RA). To some extent, this comparison may reflect the lack of inclusion of dry deposition to the LV site, since deposition fluxes include only ionic fluxes via rain and snowmelt. However, it seems quite clear that deposition at LV will remain at the very low end of the scale even if annual dry deposition increases inputs estimates by several-fold. If flux data were available for Sagehen Site 1, the N outputs would be substantially greater, judging by the tenfold higher soil solution NO₃⁻ concentrations.

Figure 5 — Atmospheric deposition and leaching of H⁺, S, and N in the Integrated Forest Study sites (Johnson and Lindberg 1991) and Site 2 in Little Valley, Nevada (LV). Stands: CP (*Pinus strobus*, Coweeta, NC); DL (*Pinus taeda* stand at Duke, NC); GS (*Pinus taeda*, B.F. Grant Forest, GA); LP (*Pinus taeda*, Oak Ridge, TN); FS (*Pinus elliotii*, Bradford Forest, FL); DF (*Pseudotsuga menziesii*, Thompson, WA); RA (*Alnus rubra*, Thompson, WA); NS (*Picea abies*, Nordmoen, Norway); HF (northern hardwood, Huntington Forest, NY); MS (*Picea rubens*, Howland, ME); WF (*Picea rubens*, Whiteface, NY); ST (*Picea rubens*, Clingman's Dome, NC); LV (*Pinus contorta/P. jeffreyi*, Little Valley, NV). Deposition fluxes at LV include bulk precipitation during the snow-free season and snowmelt inputs.



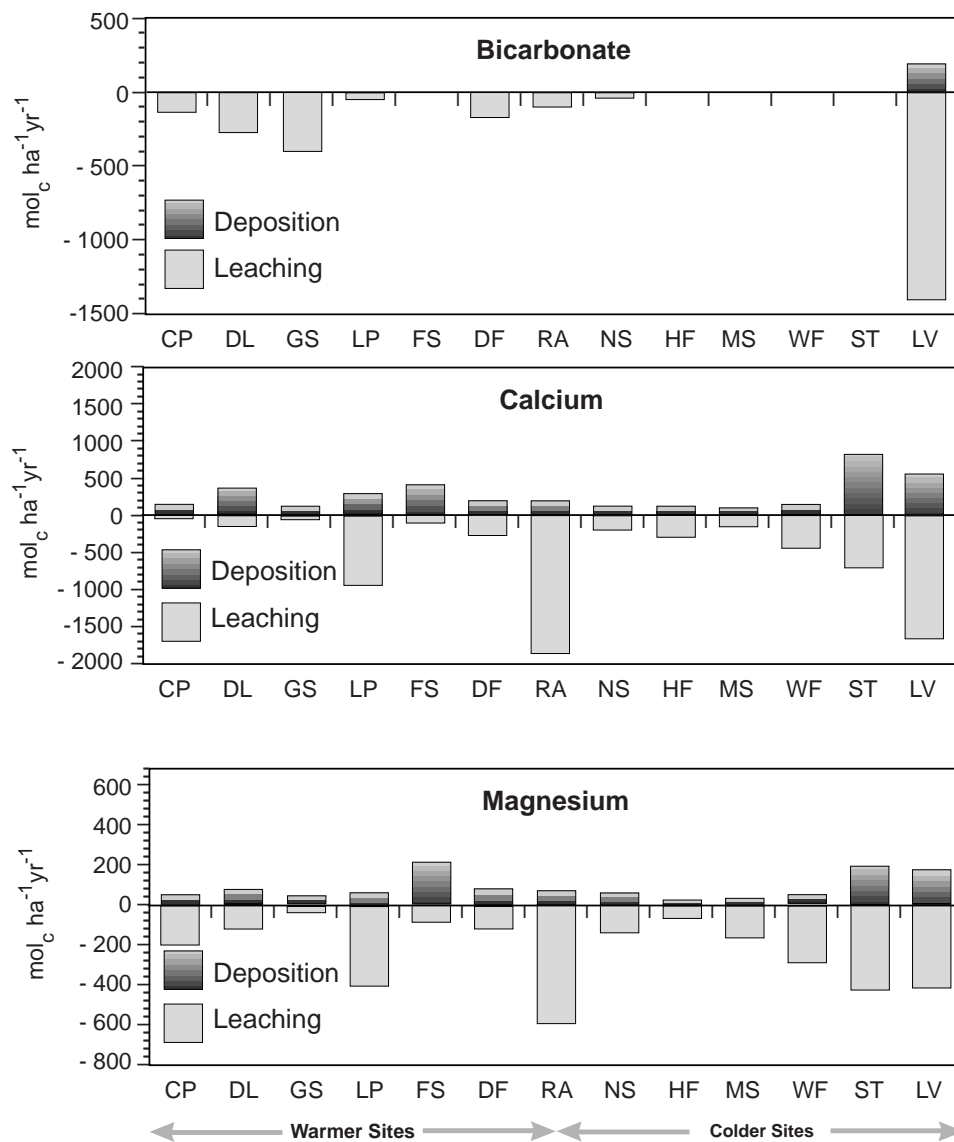


Figure 6 — Atmospheric deposition and leaching of HCO₃⁻, K, and Mg in the Integrated Forest Study sites (Johnson and Lindberg 1991) and Site 2 in Little Valley, Nevada (LV). See figure 5 for legend. Deposition fluxes at LV include bulk precipitation during the snow-free season and snowmelt inputs.

In contrast, the LV site had was in the high range for HCO₃⁻ fluxes and in the moderate to high range for Ca²⁺ and Mg²⁺ fluxes compared to the other IFS sites. The high inputs no doubt reflect high inputs of dust to the LV site from nearby desert systems, and the high outputs reflect the relatively high base saturation of the soils, high weathering rates of primary minerals, and high rates of HCO₃⁻ leaching in these systems. The LV site seems to be experiencing net losses of Ca²⁺, Mg²⁺, and K⁺ during the 1994-95 water year, but it should be noted that this was a very wet year (>200 percent of normal snowpack), and leaching fluxes in drier years are almost certainly lower. We will continue to monitor this site in both dry and wet years to develop long-term average flux values.

Conclusions

Studies to date reveal a wide range in N and P status in the four sites investigated in the eastern Sierra Nevada, with no clear patterns yet emerging. In one low-P high-elevation red fir site at Sagehen, NO₃⁻ released during snowmelt readily leached through the soil profile, suggesting the possibility of a temporal disconnection between snowmelt N release and biological uptake. In lower-elevation pine sites in Little Valley, snowmelt NO₃⁻ release was later and less concentrated, and did not penetrate through the soil profile. Streamwater NO₃⁻ pulses occurred during dry years but not wet years in both sites, however, suggesting that snowmelt NO₃⁻ shunts

around the biological system in at least part of each watershed during dry years. The differences in NO_3^- mobility among these sites may also be related to soil parent material. A large range in available soil P was evidenced among the different soil parent materials, and the degree of weathering varied. The possibility of P deficiency in the Andic soils at Sagehen is being explored.

Compared to other forest ecosystems in more humid and polluted environments, N, S, and H^+ deposition and soil leaching fluxes at the Little Valley site are extremely low, but HCO_3^- and base cation fluxes are high. These differences reveal that the Little Valley site is relatively pristine, and that ionic fluxes at this site are dominated by natural carbonic acid leaching and weathering reactions.

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References

- Berg, N.H. 1992. **Ion elution and release sequence from deep snowpacks in the central Sierra Nevada, California.** Water, Air, and Soil Pollution 61: 139-168.
- Byron, E.R.; Axler, R.P.; Goldman, D.R. 1991. **Increased precipitation acidity in the central Sierra Nevada.** Atmospheric Environment 25A: 271-275.
- Byron, E.R.; Goldman, C.R. 1989. **Land-use and water quality in tributary streams of Lake Tahoe, California-Nevada.** Journal of Environmental Quality 18: 84-88
- Bytnerowicz, A.; Riechers, G. 1995. **Nitrogenous air pollutants in a mixed conifer stand of the western Sierra Nevada, California.** Atmospheric Environment 29: 1369-1377.
- Coats, R.N.; Leonard, R.L.; Goldman, C.R. 1976. **Nitrogen uptake and release in a forested watershed, Lake Tahoe Basin, California.** Ecology 57: 995-1004.
- Cole, D.W.; Rapp, M. 1981. **Elemental cycling in forest ecosystems.** In: Reichle, D.E., ed. Dynamic properties of forest ecosystems. London: Cambridge University Press; 341-409.
- Fahey, T.J. 1983. **Nutrient dynamics of aboveground detritus in lodgepole pine (*Pinus contorta* ssp. *latifolia*) ecosystems, southeastern Wyoming.** Ecological Monographs 53: 51-72.
- Fahey, T.J.; Knight, D.H. 1986. **Lodgepole pine ecosystems.** Bioscience 36: 610-617.
- Galloway, J.N.; Schlesinger, W.H.; Levy II, H.; Michaels, A.; Schnoor, J.L. 1995. **Nitrogen fixation: Anthropogenic enhancement-environmental response.** Global Biogeochemical Cycles 9:235-252.
- Goldman, D.R.; Jassby, A.D.; Hackley, S.H. 1993. **Decadal, interannual, and seasonal variability in enrichment bioassays at Lake Tahoe, California Nevada, USA.** Canadian Journal of Fisheries and Aquatic Science 50: 1459-1495.
- Hart, S.C.; Firestone, M.K. 1989. **Forest floor-mineral soil interactions in the internal nitrogen cycle of an old-growth forest.** Biogeochemistry 12: 103-127.
- Johnson, D.W. 1995. **Soil properties beneath *Ceanothus* and pine stands in the Eastern Sierra Nevada.** Soil Science Society of America, Journal 59: 918-924.
- Johnson, D.W., Lindberg, S.E., eds. 1991. **Atmospheric deposition and forest nutrient cycling: A synthesis of the Integrated Forest Study.** Ecological Series 91, New York: Springer-Verlag; 707 p.
- Johnson, D.W.; Van Miegroet, H.; Lindberg, S.E.; Harrison, R.B.; Todd, D.E. 1991. **Nutrient cycling in red spruce forests of the Great Smoky Mountains.** Canadian Journal of Forest Research 21: 769-787.
- Klemmedson, J.O. 1975. **Nitrogen and carbon regimes in an ecosystem of young dense ponderosa pine in Arizona.** Forest Science 21: 163-168.
- Leonard, R.L., Kaplan, L.A.; Elder, J.F.; Coats, R.N.; Goldman, C.R. 1980. **Nutrient transport in surface runoff from a subalpine watershed, Lake Tahoe Basin, California.** Ecological Monographs 49: 281-310.
- Lindberg, S.E.; Johnson, D.W. 1989. **Sampling and analysis protocols and project description for the Integrated Forest Study.** ORNL/TM-11241. Oak Ridge, TN: Oak Ridge National Laboratory.
- Miller, D. F.; Walsh, P.A. 1991. **Air quality and acidic deposition in the southwestern Sierra Nevada.** Presented at the 84th annual meeting and exhibition of the Air and Waste Management Association, Vancouver, British Columbia, Canada; 1991, June 16-21; 22 p.
- Olsen, S.R.; Sommers, L.E. 1982. **Phosphorus.** In: Page, A.L.; R.H. Miller, R.H.; Keeney, D.R., eds. Methods of soil analysis. Part 2. Chemical and microbiological properties. 2nd ed. Number 9 in the Series, Agronomy. Madison, WI: American Society of Agronomy; 403-430.
- Schimel, J.P.; Firestone, M.K. 1989. **Nitrogen incorporation and flow through a coniferous forest soil profile.** Soil Sci. Soc. Amer. J. 53: 779-784.
- Stark, N.M. 1973. **Nutrient cycling in a Jeffrey pine ecosystem.** Missoula, MT: University of Montana.
- Timmer, V.R.; Stone, E.L. 1978. **Comparative foliar analysis of young balsam fir fertilized with nitrogen, phosphorus, potassium, and lime.** Soil Science Society of America, Proceedings 42: 135-130.